Coherent Phase Data Segment Layout in Data Storage Systems

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Field of the Invention

The present invention relates to organization of data in data storage systems, and more particularly, to organization of audio/video data stored in disk drives for uniform data retrieval rate.

Background of the Invention

Data storage systems such as disk drives are utilized for data storage and retrieval in a variety of applications. A typical disk drive includes a spindle motor for rotating a data disk, and an actuator for moving a head carrier that supports read/write heads radially across the disk to write data to or read data from concentric data tracks on the disk. Many disk drives include a plurality of disks separated by spacer rings and stacked on a hub attached to the spindle motor, a plurality of read/write heads, and a plurality of head carriers, each head carrier supporting at least one read/write head.

To access a data segment starting on a track, in a seek operation the head is moved radially across the tracks to the desired track where the data segment starts. Thereafter, the rotation of the disk rotates the data segment on the track under the head for writing data to or reading data therefrom. The data segment can continue onto one or more other tracks, wherein the head is sequentially moved to subsequent tracks for accessing the remainder of the data segment. The response time of the disk drive in

accessing a data segment includes the sum of three time periods: (1) the time period for the actuator to move the head to the desired track (seek time), (2) the time period for the start of the data segment to rotate under the head (rotation time or rotational latency), and (3) the time period for recording or retrieving the entire data segment (transfer time). The sum of the seek time and the rotational latency is also known as access time.

A data rate, or throughput, in a disk drive with conventional data layout, is determined as the ratio of the transfer time for the data in a selected data segment and the response time for the data segment. For a randomly selected data segment, as in a fragmented disk drive, the data rate for different data segments is random. FIG. 1 illustrates conventional layout of Logical Block Addresses (LBA) in a disk drive disk space for maximizing forward sequential throughput. The layout is optimized for data disk drives utilized for data storage in computer systems and maximizes forward sequential throughput. Each data segment DS comprises two tracks TK shown in a linear fashion. The advancing phase between sequential tracks TK as the disk rotates is selected as a rational combination of the number of sectors or LBAs per track, X. The number X is used as a modulus with a factor chosen so that the rotational time associated with the phase advance (skew), is just greater than the time for the actuator to move the head from track to track. The head movement can be either across the surface of a disk or between heads to different disk surfaces.

Such conventional layouts usually result in good performance for disk drives utilized in computer applications as measured by various well known benchmark programs. However, a disadvantage of such layouts is the poor performance of the disk drive when used for storing Audio Visual (AV) content. For example, the disk drive response time when moving sequentially backward through the content (as for reverse play or reverse search) is significantly higher than when moving forward through the

content. This is because as shown in FIG. 1, the starting and ending phase of any data segment DS, and accordingly its rotational phase relative to other data segments, is different according to its track. For a randomly selected data segment DS, the rotational phase or time to the next randomly selected data segment DS is a random variable. The phase difference (rotational phase) between the data segments is incoherent. As such, when moving the head from one data segment to another data segment, especially when serving more than one AV stream, a wide range of rotational phases and rotate times are encountered and the averages and maximum response times are adversely affected.

Further, in conventional disk drives, the seek time and the rotational latency are treated separately, though access time is more important for any application than the individual time periods. The seek time and rotational latency are combined by default through a computer file system and a default access time results for a particular system and application. Therefore, the seek time and the rotational latency are not utilized in combination for efficient operation of the disk drive in reducing access time. As such in many systems, a seek control system moves the head to a target track as fast as possible and then on average waits one half a revolution for the data to rotate under the head ("hurry up and wait"). Fast movements of the head result in unwanted acoustic noise, and lead to high power consumption.

In some disk drives an attempt has been made to overcome the above problems by engineering the file system. However, the disk drive designer has incomplete knowledge of the physical layout of the data disk, and such knowledge can quickly become obsolete. As a result, the disk drives are overdesigned as described above, with resulting cost penalties. Still other attempts have been made to overcome the rotational latency and seek time disconnect. One such attempt is seek reordering wherein the order of requests to the disk are reordered to minimize the access time

over several such requests. Though this method can be effective in disk drives utilized in computer systems for computer applications, it is quite ineffective for support of multiple AV streams. This is because the isochronous nature of AV streams makes order of requests for multiple AV streams important. As such, changing the order of requests results in failure to record or retrieve the correct AV data at the correct time.

There is, therefore, a need for a system and method for improving the systematic reliability of response time and consequently the sustained throughput of disk drives. There is also a need for such a system and method to allow for improvement in managing seek acoustic noise.

Summary of the Invention

The present invention satisfies these needs. In one embodiment the present invention provides a method and data layout/pattern for organizing and allotting disk drive capacity in a data storage system including data storage media having at least one recording surface. A method for storing at least one set of data segments to said recording surface in concentric data tracks includes the steps recording each data segment onto said recording surface such that each stored data segment has a start, an end and a rotational phase from that data segment to each of the respective ones of all other data segments, wherein the data segments are recorded with coherent relative rotational phases. The coherent phase layout provides substantially constant data transfer rate to/from the storage media because the relative rotational phase or rotational time from one data segment to another data segment is deterministic.

The relative rotational phases are predetermined, and each relative rotational phase can have one of a limited number of predetermined values. In one version, the relative rotational phases from each data segment to respective ones of a first subset of the data segments in the set have one of said predetermined values, and the relative

rotational phase from that data segment to respective ones of a second subset of the data segments in the set have another of said predetermined values. Each data segment can include one or more tracks, and data tracks in that data segment can be offset by a predetermined skew angle. Alternatively, each track can include one more data segments.

In one version, one or more incoming data streams are received and partitioned into data segments for storage in coherent phase. The data segments are recorded so as to obtain a nearly constant data storage transfer rate when reading the data from the data storage media. The data segments read from the storage media are combined to reformulate one or more data streams from the data segments. In one embodiment of the present invention, the data storage system is a component of a computer system. In another embodiment, the data storage system can be a component of an audio video storage server. In that case, the data segments comprise audio visual data and the method of the present invention is used to store and retrieve isochronous Audio-Video (AV) content for consumer electronics applications.

The present invention further provides a seek profile for disk drive including a transducer radially moveable relative to the tracks on a disk by an actuator controlled by a servo circuit during a seek operation from a starting segment to a destination segment. Data is stored on the disk in segments with the coherent phase layout. Performing a seek operation from a starting segment to a destination segment includes obtaining a seek profile for controlled application of current to the actuator based on the seek profile, wherein the seek profile includes constraints for the seek operation as a function of: (1) a seek distance representing the radial distance between the starting and destination segments, and (2) a seek time based at least on the relative rotational phase between the starting and destination segments. Current is then applied to the actuator as a function of said constraints to perform the seek operation. In one version,

each seek operation is completed at the expiration of the respective seek time, and for at least one set of seek distances, the respective seek times are predetermined. Further, the seek time between two data segments can be based on the relative rotational time between the data segments, wherein regardless of the seek distance between the two data segments, the seek operation need only be completed at the end of the respective seek time, not before. As such, in one version, wherein a set of data segments have the same inter-segment rotational time (or relative rotational phase), the seek time for each seek operation among two data segments in the set is the same, and preferably equal to said inter- segment rotational time. The actuator need only move the transducer as fast as needed to cover the seek distance by the end of the seek time, and not before. Therefore, for short seek distances in relation to long seek distances, the actuator moves the transducer at a lower velocity than for long seek distances, to cover the seek distance at the end of the seek time. This reduces seek acoustic noise.

The present invention improves the systematic reliability of response time and consequently the sustained data rate or throughput, taking into account the electro-mechanical nature of a disk drive. At the same time the present invention preserves the random access nature of a disk drive, and the new benefits derived therefrom for the storage of AV content. Additionally, the present invention allows for significant improvement in managing seek acoustic noise.

Brief Description of the Drawings

These and other features, aspects and advantages of the present invention will become better understood with regard to the following description, appended claims and accompanying drawings where:

FIG. 1 shows a conventional disk track layout for a disk drive;

FIG. 2 shows an example computer system including a disk drive with a data

pattern layout according to one aspect of the present invention;

FIG. 3 depicts a top plan view of a disk drive head and disk assembly (HDA) and a block diagram of disk drive electronics of the disk drive of FIG. 2 that implement and utilize principles of the present invention;

FIG. 4 shows a block diagram of the architecture of an embodiment of the drive electronics of the disk drive of FIG. 2;

FIG. 5 shows an embodiment of data pattern layout in a linear fashion for the disk drive according to the present invention;

FIG. 6A shows an embodiment of data pattern layout of FIG. 5 in concentric tracks according to the present invention;

FIG. 6B shows an embodiment of data pattern layout in different recording zones;

FIG. 7A shows a functional diagram of an aspect of the servo controller of FIG. 4 operating from seek and transducer motion information in seeking operations;

FIG. 7B shows an example flow diagram of an embodiment of steps for performing seek operations according to the present invention;

FIG. 8A shows example performance values for a disk drive according to the present invention;

FIG. 8B shows a plot of performance indicia for a disk drive according to the present invention;

FIG. 9 shows an example block diagram of and AV storage server and AV system according to another aspect of the present invention;

FIG. 10 shows a flow diagram of an embodiment of a process for storing data in a disk drive according to the present invention;

FIG. 11 shows a flow diagram of an embodiment of a process for retrieving data in a disk drive according to the present invention;

FIG. 12A shows another embodiment of a data pattern layout in a linear fashion, according to the present invention, wherein each data segment is one-half track in size;

and

FIG. 12B shows another embodiment of a data pattern layout in a linear fashion, according to the present invention, wherein each data segment is one-third track in size.

To facilitate understanding, identical reference numerals have been used, where possible, to designate identical elements that are common throughout the figures.

Detailed Description of the Invention

FIG. 2 shows a block diagram of an example computer system 10 in which a method embodying aspects of the present invention can be implemented. The computer system 10 includes a central processing unit ("CPU") 14, a main memory 16, and I/O bus adapter 18, all interconnected via a system bus 20. Coupled to the I/O bus adapter 18 is an I/O bus 22 that can comprise e.g. a small computer system interconnect (e.g., SCSI, ATA (IDE), 1394, etc.) bus, and which supports various peripheral devices 24 including a storage device/unit such as a disk drive 25. The disk drive 25 includes drive electronics 26 and a head disk assembly 28 ("HDA"). The computer system 10 can further comprise a network interface device 30 connected to the bus 20 for data communication between the computer system 10 and other computer systems 32 via a network link 34 in a networked data processing system 36.

FIG. 3 depicts a top plan view of the HDA 28 and the drive electronics 26 of the disk drive 25, incorporating principles and aspects of the present invention therein. The HDA 28 includes a rotatable magnetic storage disk 38, a DC brushless in-hub spindle motor (not specifically shown), a hub 40 containing and/or enclosing the spindle motor and spindle bearings, a rotary voice coil actuator assembly 42, a read preamplifier/head select/write driver circuit 44 connected to the rotary actuator by a flex circuit 46 enabling the HDA 28 to be connected to the disk drive electronics 26 mounted to the HDA 28

externally of the interior thereof, and a base housing 50 to which the various components of the disk drive are mounted and aligned.

Typically, the storage disk 38 is coated with a magnetic material that stores data in the form of longitudinal bipolar magnetic patterns written by digital saturation recording techniques within each concentric data track. For simplicity, the following discussion mentions only a single storage disk 35 in the disk drive 25. However, as those skilled in the art will recognize from the following discussion, the present invention is capable of use in disk drives having multiple disks mounted upon the spindle hub 40, the number of disks 38 and associated data transducer heads affecting the vertical height of the disk drive.

The actuator assembly 42 conventionally comprises a transducer head gimbal assembly 52 for each disk data surface, a carriage assembly 54, and a rotary voice coil actuator motor (VCM) 56. In the rotary-type actuator assembly 42, the transducer head gimbal assembly 52 is attached to an outer end 58 of the carriage 54, while the actuator motor voice coil 56 is attached at a hub end 60 of the carriage 54. Centrally located along the carriage is a pivot 62 about which the actuator assembly rotates on a dual bearing assembly secured to the base housing 50. The pivot 62 is located adjacent the storage disk 38 such that the carriage 54 extends the upper and lower transducer head gimbal assemblies 52 over the surfaces of the storage disk 38. Consequently, selective activation of the actuator voice coil motor (VCM) 56, rotates the actuator assembly 42 about the pivot 62 and accurately positions each transducer assembly 52 over the surface of the storage disk 38. As such, data can be written to, and can be read from, each data storage surface of the storage disk 38 by transducers within the transducer assembly 52.

Typically, the transducer assembly 52 includes a dual head transducer assembly

64 including e.g. a thin film inductive write head and a shielded magnetoresistive thin film read element (not shown). The dual head transducer assembly 64 is formed at an outer end of one rail of e.g. a two rail aerodynamic slider 70, as shown for example in FIG. 3. In accordance with conventional practice, the magnetoresistive (MR) read element is formed on the slider first, in order to take advantage of the smoothness of the finished slider end surface. After the MR read element is formed, the thin film inductive element is formed over the MR read element.

A flexure assembly 72 includes a gimbal secured to the slider and to a load beam. The load beam provides a preloading gram force to the slider to bias it toward the facing disks storage surface. The flexure assembly 72 connects at one end to the carriage; another end supports a slider 70 and the read/write elements over the disk surface. When the storage disk 38 is not rotating, the slider 70 and transducer assembly 64 rest upon a radially inward landing zone of the disk surface. On the other hand, when the storage disk 38 is rotating, the slider 70 overcomes the load beam spring bias and "flies" several microinches above the disk surface on an "air bearing" in accordance with what is known in the art as Winchester technology.

During flight, the actuator assembly 42 positions the transducers in the transducer assembly 64 over the multiplicity of concentric data tracks 74 and data segments DS defined on one, or the oppositely facing, storage surface of the storage disk 38 so as to read servo and user data and to write user data. However, when the disk drive 25 is deactivated, the sliders 70 are moved in unison by the carriage assembly 54 to the inner landing zone and "parked" such that they will not damage the surface of the disk 38 by coming into contact with it.

The disk drive preamplifier/write driver circuit 44 is connected, via a flex circuit 78, to the actuator assembly 42 so that electrical signals may reach the head

transducer assemblies 64 via minute wires carried along the side of the carriage 54 and load beam. The signals leaving and entering the HDA 28 via the flex cable 46 are utilized by a drive microcontroller 80 and other electronics including a motors control driver ASIC 82 which supplies driving signals to operate the spindle motor and the rotary actuator, a PRML read/write channel 44 which receives and decodes coded data from the disk and which encodes and delivers coded data to the write driver portion of the IC 44.

A disk drive electronics ASIC 84 implements a SERDES/ENDEC function, and ECC function, a data sequencer, a memory controller, a bus level interface, and a microprocessor interface for interfacing the microprocessor 80 with other circuits including a DRAM buffer 86 which can include microprocessor program instructions, seek profiles, data blocks being transferred between a host (not shown) and the data storage disk 38, etc.. The microprocessor 80 implements a servo loop for controlling positioning (following, seeking, etc.) of the rotary actuator 42. In one example, the memory 86 includes program instructions for execution by the microprocessor 80 to implement the servo loop.

During track settling and following operations, the servo loop receives actual position samples from position information within embedded servo wedges via the read element, and separately estimates head position, velocity and actuator bias force in order to generate and put out a control command value via the motors control ASIC 82 to control head position. During each seek operation from a starting track/segment to a destination track/segment, the servo loop utilizes a seek profile in conjunction with head motion information (e.g., position, velocity, etc.) to determine the control command value for moving the transducers from the starting track/segment to the destination track/segment. An internal data, address, control bus structure 88 interconnects the microprocessor 80, motors control ASIC 82, PRML read/write channel ASIC 44, disk

drive electronics ASIC 84 and DRAM buffer chip 86. A connection to the host computing equipment is provided by a drive interface bus 90.

Referring to FIG. 4 in conjunction with FIG. 2, in another embodiment, the drive electronics 26 of FIG. 4 is shown to include a data controller 92 interconnected to a servo controller 94 via bus 96, and a read/write channel 98 interconnected to the data controller 92 via a data buffer bus 100. Actual positioning information from data disks are induced into the transducers, converted from analog signals to digital data in the read/write channel 98, and transferred to the servo controller 94, wherein in a servo loop the servo controller 94 utilizes the head positioning information for performing seeking and tracking/following operations of transducers over the disk tracks 74. In one example, the servo controller can include the microprocessor 80 of FIG. 3, for executing program instruction to implement the servo loop.

A typical data transfer initiated by the CPU 14 to the disk drive 25 may involve for example a direct memory access ("DMA") transfer of digital data from the memory 16 onto the system bus 20 (FIGS. 2 and 4). Data from the system bus 20 are transferred by the I/O adapter 18 onto the I/O bus 22. The data are read from the I/O bus 22 by the data controller 92, which formats the data into data blocks with the appropriate header information and transfers the data to the read/write channel 98. For example, the data controller 92 collects data into data blocks or segments and appends Error Detection and Correction bits to the blocks. These blocks are further collected into a service unit which is then passed to the read/write channel 98. Concurrently, a command is issued to the servo controller 94 to cause the actuator 42 to move the actuator assembly 64 to the appropriate cylinder. One or more of said function can be implemented external to the disk drive as a software driver running in a host processor (e.g., CPU 14), such as for simple ATA disk drives. The read/write channel 98 operates to convert data between the digital form used by the data controller 92 and the analog

form suitable for writing to data disks by transducers in the HDA 28.

For a typical request for transfer of data from the HDA 28 to the CPU 14, the data controller 92 provides a disk track/segment location to the servo controller 94 where the requested data is stored. In a seek operation, the servo controller 94 provides control signals to the HDA 28 for commanding the actuator 42 to position the transducer assembly 64 and transducers therein over said disk track/segment for reading the requested data therefrom. The read/write channel 98 converts the analog data signals from the transducers into digital data and transfers the data to the data controller 92. The data controller 92 places the digital data on the I/O bus 22, wherein the I/O adapter 18 reads the data from the I/O bus 22 and transfers the data to the memory 16 via the system bus 20 for access by the CPU 14.

Referring FIG. 5, in one embodiment of the present invention, each surface of a disk 38 carries a multiplicity of spaced apart concentric tracks 74. Each track 74 is divided into an equal number of circumferential divisions. These divisions are generally arced along the disk radius in accordance with an arc defined by the head and the rotary actuator. Each division begins with a servo sector or "wedge" and is followed by a user data sector. The head position servo information is included in each servo wedge and the user data is recorded in each data sector. Because the servo information is included on the data surface, the servo sectors are said to be "embedded" in that they lie interspersed among the data sectors. Each servo wedge contains information used for accurate positioning of the transducers over each selected data track, so that user data may be written to, or read from, an adjacent data sector.

As shown in FIG. 5, in one embodiment of the present invention data segments DS including user data are stored on the disk 38, wherein each data segment DS

comprises one or more tracks 74. FIG. 5 shows an example track layout on the disk 38 in a linear fashion, wherein the data segments DS have coherent phase. As such, each data segment DS has a start "S", an end "E" and a relative rotational phase "R" relative to other data segments DS. Each data segment DS has a predetermined rotational phase to another data segment DS. For each data segment DS, the rotational phase R from that data segment DS (e.g., end of the data segment) to each of the other data segments DS is predetermined, and can be selected from a limited range of values. As such, if a set of data segments includes ten data segments, each data segment DS has a distinct, but no necessarily different in value, predetermined rotational phase R relative to each of the other nine data segments in the same. In that example, two or more of the nine distinct relative rotational phases from said one data segment to the other nine data segments in the set can have the same predetermined value (e.g., FIG. 5). Further, different subsets of the nine rotational phases can have different predetermined values (e.g., FIGS. 12A-B).

A phase difference between the start of a data segment DS and the start of another data segment DS is defined as a relative start phase (e.g., 0 in FIG. 5), and a phase difference between the end of a data segment and the end of another data segment is defined as a relative end phase (e.g., 0 in FIG. 5). In one layout version, the relative rotational phase of any data segment to any other data segment DS is independent of the start or end tracks of the data segments DS. Similarly, the relative start phase for any data segment DS is predetermined, and the relative end phase for any data segment DS is also predetermined, independent of the start or end tracks of the data segment DS.

In the example layout shown in FIG. 5, the start of each data segment DS is defined as 0, and the end of each data segment DS is defined as 360+(N-1)xα, where N is the number of tracks 74 in a data segment DS and α is the skew angle between

tracks within a Data segment DS. The rotational phase distance R from the end of a data segment DS to the start of any subsequent data segment DS, adjacent or otherwise, is predetermined and the same (e.g., R=360-(N-1)xα). As such, the rotation time period from the end of a data segment DS to start of any subsequent data segment DS (inter-segment rotational time) is predetermined and the same. The skew angle α is selected to be greater than or equal to track-to-track seek time (e.g., between about 0.2x360 to about 0.3x360 degrees). The skew angle α can be adjusted to refine average and worst case response times. In FIG. 5, for the data segment DS, the starts are the same and constant (i.e., 0 degrees), the ends are the same and constant (i.e., 360+α degrees), the relative start and end phases are the same and constant (i.e., 0 degrees), and the relative rotational phased R are the same and constant (i.e., 360-α degrees).

The rotational phase R can be adjusted to allow skew angle between tracks for a given number of tracks per data segment DS to improve the average response time for a randomly selected data segment DS. Preferably, the skew between tracks within a data segment (e.g., the rotational angle between start of tracks, or the resulting track-to-track seek time -- track head switch time) is selected to be just greater than the maximum time for the actuator to move the head the distance of one track.

FIG. 6A shows another diagram of example track layout of FIG. 5,and FIG. 6B shows an embodiment of data pattern layouts in different recording zones 91, described further below. Referring to FIGS. 5 and 6A, data segment DS0 comprising tracks TK0, TK1; data segment DS1 comprising tracks TK2, TK3; data segments DS2 comprising tracks TK4, TK5; and data segment DS3 comprising tracks TK6, TK7 are shown. Tracks TK0, TK2, TK4 and TK6 have the same start and end relative to each other. And, tracks TK1, TK3, TK5, and TK7 have the same start and end relative to each other. The skew angle between track pairs TK0, TK1 is shown as α. Similarly, the

skew angle between track pairs TK2, TK3; TK4, TK5; and TK6, TK7, is shown as α. In this example, for each data segment DS the rotational phase R, or rotational time, to a subsequent data segment is always the same (i.e., 360-α).

To provide a substantially constant data transfer rate, a seek profile for the servo system can be designed according to seek time constraints such that the seek time between any two data segments in a set of data segments (e.g., data segments in a recording zone 91) is selected to be a predetermined value. For example, the seek time can comprise the maximum seek time that is necessary to seek from one data segment DS to another data segment DS. As such, if for example 10 msec is required to seek from DS0 to DS1, then seeking from DS1 to DS4 also requires 10 msec. For short seeks (e.g., DS0 to DS1) compared to long seeks (e.g., DS0 to DS11), the servo system can take the entire 10 msec for the seek operation and move the head slower by inputting less power into the actuator (thereby reducing acoustic noise). Other predetermined seek times can also be selected to achieve substantially constant data transfer rate to and from the disk.

When the seek performance requirement is so selected, the seek noise can accordingly be reduced significantly. This is a highly valuable attribute for hard disk drives in A/V systems and A/V applications. For example, seek acoustic noise can be dramatically reduced by implementing a specification for the seek servo system (seek profile) according to Table 1 below. Additionally, the cost of seek servo amplifier and actuator motor can be reduced.

Seek Distance	Seek Time
One track and head switches (for intra-DS moves)	2 msec
Two tracks to two thousand tracks	8 msec
Two thousand one tracks to full stroke	19 msec

Table 1. Example seek servo spec. for coherent data segment layout

In the context of Audio and/or Video data and streams, when the data is organized according to the present invention, the seek performance requirement is systematically relaxed. The average and worst case response times are improved. The reduction of the average and worst case response time is also a benefit of the present invention in cases where e.g. a large number of simultaneous streams are being serviced and/or the content has become fragmented physically.

In one embodiment, as a result of a data segment layout according to the present invention, wherein the rotational phase R (and inter-segment rotational time) from a data segment DS to the start of any subsequent data segment DS is predetermined (e.g., the same, or selected from a limited number of predetermined values, etc.), seeks requiring less time than the inter-segment rotational time need not be completed any faster. As such, the seek time is selected based on the inter-segment rotational time, allowing a larger number of possible seek distances can be completed within an inter-segment rotational time.

An example servo loop implementing predetermined seek times according to the present invention is now described. Referring back to FIG. 4, for each seek operation to transfer data, the data controller 92 provides a destination track/segment DS (in

relation to the current position of the head at a starting track/segment DS), to the servo controller 94 where data is to be transferred to/from a segment DS. The servo controller 94 provides control signals to the HDA 28 for commanding the actuator 42 to position the transducer over said destination track/segment DS for transferring data. For example, for a read operation, the read/write channel 98 converts the analog data signals from the transducers into digital data and transfers the data to the data controller 92. The data controller 92 places the digital data on the I/O bus 22, wherein the I/O adapter 18 (FIG. 2) reads the data from the I/O bus 22 and transfers the data to the memory 16 via the system bus 20 for access by the CPU 14.

In one version, the servo controller 94 implements a servo loop, and uses seek profiles for performing seek operations. For each seek operation from a starting track/segment DS to a destination track/segment DS, the servo controller 94 receives actual position samples from position information within embedded servo wedges via the read element in the head, then estimates head position and velocity, and uses a seek profile to generate and put out a control command value Icommand to the actuator VCM to move the transducers from the starting track/segment DS to the destination track/segment DS.

Destination segment DS position data on bus 96 provides coarse positioning information to the servo controller 94 for specifying a seek distance representing the radial distance that the actuator 42 must move the transducer from the starting segment DS (e.g., end of starting segment) to reach the destination segment DS (e.g., start of destination segment). The seek time comprises a predetermined time period for the transducer to cross over the tracks between the starting segment DS and the destination segment DS in the seek distance. The servo controller 94 uses seek information, including e.g. seek distance, on bus 96 and servo head position information on line 99 to generate a current value $I_{COMMAND}$ according to the seek

profile, to control supply of input actuator current I_a to the VCM, resulting in controlled movement of the actuator assembly 64 such that the seek operation is completed by the end of the seek time, and preferably not sooner. As such, according to the seek profile, the servo controller 94 generates the current command value Icommand such that each seek operation is completed at the expiration of the respective predetermined seek time.

For the example layout pattern of FIG. 5, the seek time is selected to be the relative rotational time (inter-segment rotational time based on relative rotational phase R) between segments DS. Because in the pattern of FIG. 5 the relative rotational phase R for all the segments DS in the same, the seek time from each starting segment DS to any destination segment DS is the same, regardless of the seek distance in tracks between the starting and destination segments. Seeks requiring less time than the inter-segment rotational time need not be completed any faster. Accordingly, if for example 20 msec is required to seek from DS0 to DS2, then seeking from DS1 to DS4 also requires 20 msec. For short seeks (e.g., DS0 to DS1) compared to long seeks (e.g., DS0 to DS11), according to an example seek profile the servo controller 94 uses the entire 20 msec for the seek operation and moves the head slower by inputting less power into the actuator (thereby reducing acoustic noise). As such, according to the example seek profile, for short seeks the servo controller 94 commands less current input to the VCM to move the actuator, and for longer seeks, the servo controller commands more current input to the VCM to move the actuator faster. In either case, the seek distance is traversed by the transducer such the each seek operation is completed by the end of the same seek time, and not sooner.

The seek profile can include constraints such as feed current values, target velocity per distance, expected distance to go, etc. for seek operations. In one version of the servo controller 94, for each seek operation, using the seek distance and the

predetermined seek time for the seek operation, the servo controller 94 obtains current level constraints from the seek profile, to generate the current command for the seek operation. Then, during the seek operation, the servo controller 94 receives actual head position information, and compares the actual head position information with the expected head position information according to the seek profile, and adjusts the current command value to the actuator 42 as necessary to move the transducers according to the seek profile, such that the seek is completed by the end of the seek time, not necessarily sooner.

For generating the current command, in one embodiment a feed current value FC is obtained or calculated by a microcontroller (e.g., microprocessor 80 in FIG. 3) in the servo controller 94 to provide a base current value, depending upon the seek distance and seek time. The feed current value FC is an a priori prediction of current expected to be required to carry out the seek operation to achieve the seek performance described herein (e.g., Table 1) based on a data layout according to the present invention. It is based on information which quantify the operating characteristics, some of which are developed during initialization calibration routines, and can be stored in memory. The feed current value FC allows more accurate adherence to a desired seek trajectory. The feed current value FC corresponds to the actuator current needed to keep the actuator on the idealized trajectory.

In this example, fundamentally, a nominal current waveform is preestablished for each seek distance to be traversed by the expiration of the respective predetermined seek time (preferably not sooner), wherein the seek time is based e.g. on the relative rotational phase R (or inter-segment rotation time) between the starting segment DS (e.g., end of starting segment) and the destination segment DS (e.g., start of destination segment).

In versions where all segments DS in a set of segments have the same relative rotational phase R (e.g., FIG. 5), the seek time can be the same for all seek distances between all segments DS in that zone. In versions where the relative rotational phase between a set of segments DS (e.g., segments in a recording zone 91) has one of several predetermined values (e.g., FIGS. 12A-B), the seek time can have one or more predetermined time values based at least on the values of the relative rotational phases (e.g., seek time can be a linear function of inter-segment rotation time). The seek time can also be selected to be a maximum, minimum, or combination of said predetermined time values for all seek distances.

FIG. 7A shows an example functional block diagram of an embodiment of the servo controller 94 including the microcontroller 80 of FIG.3, as configured by process steps according to the present invention to perform seek operations according to seek profiles 93, operating from seek and transducer motion information including e.g. actual head position, transducer velocity, transducer distance to destination segment DS, etc. in seeking operations. In this example the seek profile 93 includes e.g., a priori feed current values FC 93A, expected velocity/position reference values 93B, etc. The a priori feed current values FC for the basic current corresponding to the seek distance and seek time can also be calculated by the microcontroller 80 based on seek information which can reside in memory.

In one example, the feed current values FC (e.g., current profiles) are stored in memory as a FC look-up table of entries 93A, wherein each entry includes a current value FC, indexed by the seek distance and the seek time. Each feed current profile comprises an a priori prediction of current expected to be required to carry out a seek operation (e.g., transducer traversing a seek distance) by the end of the respective seek time, not sooner. In one version of the servo controller 94, for each seek operation, using the seek distance and the predetermined seek time for the seek

operation, the servo controller 94 obtains current level constraints from the seek profile, to generate the current command for the seek operation. Then, during the seek operation, the servo controller receives actual head position information, and in a regulation process 95 compares the actual head position information with expected head position information 93B (EV) according to the seek profile, and adjusts the current command value in a regulate FC process 95 as necessary to move the head according to the seek profile, such that the seek is completed by the end of the seek time, not necessarily sooner.

In another version of the servo controller 94, for each seek operation, using the seek distance and the predetermined seek time for the seek operation, the servo controller 94 obtains current level from the seek profile 93, to generate the current command for the seek operation. Then, during the seek operation, the servo controller receives actual head motion information, and compares the actual head motion information with the according to the seek profile, and adjusts the current command value as necessary to move the head according to the seek profile, such that the seek is completed by the end of the seek time, not necessarily sooner. For example, the expected values can include transducer motion constraints such as target velocity, expected velocity, expected target velocity per distance, expected distance to destination segment DS, expected transducer position, etc. in a table 93B.

In one implementation, an actuator feed current profile FC in table 93A is predetermined and provides the amount of actuator current per distance from the destination track. The predetermined look-up table 93B specifies the expected transducer velocity per distance from the destination track, EV, for each predetermined seek time. As such, in the regulation process 95, for each detected transducer location, a detected radial velocity is subtracted from the corresponding expected radial velocity. The difference is then used to adjust the profile current value for that detected

transducer location to provide the feed current values FC such that the seek distance is traversed by the end of the seek time.

FIG. 7B shows an example flow diagram of an embodiment of steps performed by the servo controller 94 for performing seek operations. The microcontroller 80 in the servo controller 94 executes program instructions including the regulation process 95. For a seek operation, the microcontroller 80 obtains the distance between the transducer location and the destination track/segment (seek distance), and obtains the seek time for the seek operation (step 101) . In one example, the predetermined seek time between each pair of segments DS (e.g., identified by unique number or location on reference disk) in a recording zone is stored in memory. In another example, the predetermined seek time between each pair of segments DS is obtained based on the inter-segment rotational time between the two segments DS using the angular location of the end of the starting segment DS and the angular location of the start of the destination segment DS on the recording surface (i.e., relative rotational phase R). The microcontroller 80 then obtains a corresponding FC value from the FC look-up table 93A using the seek distance and the respective predetermined seek time (step 103).

The microcontroller 80 used actual head position information, and subtracts current head position track from the destination segment track to determine a total number of tracks remaining to be crossed (step 105). The microcontroller 80 calculates the actual radial velocity of the transducer as the number of tracks crossed over by the transducer in between two sampling intervals (step 109), where a sampling interval is defined by a servo wedge passing under the transducer head. As such, during each sampling interval, the transducer location is detected, and the microcontroller 80 calculates the radial velocity of the transducer by determining a difference in the number of tracks between: (1) a first transducer location detected during a present sampling interval, and (2) a second transducer location detected

during a preceding sampling interval. The microcontroller 80 determines the track difference between the two transducer locations to obtain the number of tracks crossed over by the transducer between the two sampling intervals, providing a measure of the actual radial velocity of the transducer. The radial velocity can be expressed as tracks crossed over per sampling interval (e.g., tracks/sample).

The actual velocity and distance to go values are applied to address and compare to an expected trajectory value (e.g., velocity per distance remaining) stored in the trajectory profile look-up table (e.g. table 93B) in memory (e.g. DRAM 86) (step 111). A ratio value, Vr, of actual velocity value and the reference velocity value from said look-up table is calculated (step 113) in order to normalize the difference between the actual velocity and the reference velocity irrespective of magnitude thereof. The feed forward waveform value FC corresponds to the actuator current needed to keep the actuator assembly 64 on the idealized trajectory.

The normalized, signed velocity signal Vr is added to the feed forward value FC to correct for any deviations from the reference trajectory due to friction, torque constant variation, etc. (step 115). As such, the normalized error signal Vr is added to the priori feed forward value FC which yields a corrected actuator current command value $I_{Command}$. The process is repeated till the destination track/segment DS is reached (step 107). Other methods of implementing servo loops to perform the seek operations based on predetermined seek times according to the present invention are possible, and contemplated by the present invention. For instance, an example feed current calculation based on expected velocity is described in the commonly assigned United States Patent No. 5,005,089, titled "High performance, high capacity micro-Winchester disk drive", incorporated herein by reference, and can be modified to implement seek operations according to the predetermined seek times described herein.

According to the present invention, seek profile specification is given by required seek time performance across the tracks on the disk, wherein in one example the seek time is stepped (rather than conventional linear function) with a seek time for 1 track seeks, another seek time for seek distances of 2 to x tracks, another seek time for seek distances greater than x by less than y, etc. (e.g., Table 1). As such, excitation of the electromechanical system of the servo control can be relaxed, making the disk drive quieter. Using a coherent phase data layout pattern according to the present invention. A seek profile is selected to move the transducer from a starting segment to arrive at a track where the destination segment starts, just before the start of the destination segment rotates under the transducer, not sooner.

Preferably, the seek time is substantially equal to the inter-segment rotational time between the end of the starting segment to the start of the destination segment. For example using Table 1 above, to seek from a starting segment to a destination segment, the servo controller 94 determines how far the destination data segment is in tracks (seek distance), and then if the seek distance is within e.g., 2 - 2000 tracks, the transducer can take 8 msec to get to the destination segment (seek time = 8 msec). If the seek distance is more than 2000 tracks, then the seek time is 19 msec. As such, according to one version of the present invention, transducer position information from the read/write channel, the physical layout of the data with coherent phase, and the servo loop using seek times based on inter-segment rotational time, are used together to obtain nearly constant data transfer rate, and operate the disk drive quietly and with reduced power.

A data segment DS can be selected to be the amount of physically contiguous data (e.g., bytes, sectors, tracks, etc.) recorded or retrieved to or from the disk 38 each time the actuator moves the heads 52 (e.g., in a skip-sequential manner). A data segment DS is distinguished from a File Allocation Unit (FAU) used in the context of file

systems for computer applications (a data segment DS can include an FAU). The latter is usually contiguous but much smaller in size than a data segment DS. An FAU is typically between e.g. 4096 and 8192 bytes (8 to 16 sectors) while a data segment DS is between e.g. 131 Kbytes (256 sectors) to more than 1 Mbytes (several thousand sectors or several tracks), or more. Preferably, the size of a data segment DS is selected by balancing among factors including: (1) preservation of the (forward sequential) throughput of the disk drive 25, (2) budgeting for error event management, (3) the size (and cost) of a DRAM cache buffer 86 in the disk drive 25, and (4) retaining the random access nature of the disk drive 25. An example selection can be two or more tracks per data segment DS. Generally, though not necessarily, all data segments DS are of the same size. The data segments can be of different sizes, but with coherent phase.

In one version of the present invention, coherent phase can be forced on data segments DS with the choice of number of tracks per data segment size. The cache buffer size can also be adjusted to be larger than may otherwise be needed to take advantage of random access storage. In disk drives utilizing Variable Frequency Recording (VFR) (e.g., FIG. 6B), wherein track density varies radially, in recording zones at the inner most tracks there are n sectors (blocks) per track and in recording zones at the outer most tracks there are about 2n sectors per track. Tracks in between vary substantially piece-wise linearly. Preferably, the number of tracks per data segment DS is selected to vary linearly by radius. Therefore, a coherent phase data segment layout according to the present invention for seek time, and worst case response time or throughput performance, can be adjusted according to the possible seek distances and times for each VFR location on the disk 38.

Advantageously, a coherent phase data segment layout of the present invention provides the same forward and reverse sequential performance for data segment

access. The substantially identical performance for forward and reverse sequential access is advantageous for AV 'trick-play' features, as for example fast-forward and fast-reverse searching through an AV content object. As such, the present invention affords more consistent response time, and thus data rates, particularly important for fast-reverse searching.

FIG. 8A shows the disk drive performance for various e.g. intra-data segment track skew angle α selections for data segments DS, and resulting inter-data segment rotational phase R (inter-segment rotational time). FIG. 8B shows a plot of the ratio of inter-segment rotational time on average seek time versus average data rate according to the present invention. This example shows how to optimize the skew time for performance, wherein:

skew time = A x Trev;
Trev = time per revolution;
A = skew factor / skew modulus;
skew factor comprises the integer number of sectors that are used to set the skew angle or time;
skew modulus comprises the integer number of sectors into which a rotation of the disk is divided;
skew angle $\alpha = A$ x 360 degrees;
Rotation phase = (1-A) x 360;
Rotation time = (1-A) x Trev -- i.e. the time for the disk to rotate to the start of the next Data segment DS;
Rotation on Avg Seek Time = (Rotation time) / (Avg seek time);
Avg Rate = (data per DS) / (Avg Seek time + Rotation time + time to transfer data);

Skew modulus can be less than or equal to the number of servo samples per

track because a disk drive system cannot resolve time or phase below that interval. As such, *A* is a rational number between 0 and 1. The skew modulus and the skew factor are selected for a desired rotational time. Preferable selections provide an inter-segment Rotational time to the next data segment DS of about the same as the average seek time for the actuator servo system. This can be used as a guide for designing data layout and seek profiles for disk drive systems with different parameters and geometry.

Because the present invention offsets many negative aspects of rotational latency, lower spindle speed disk drives are possible. As discussed herein, access time is the sum of seek time and rotate time, response time is the sum of access time and transfer time, and data rate is the ratio of the data transferred to the response time. As rotate time after seek arrival (rotational latency) is nearly zero due to a data segment layout according to the present invention, rotate time is effectively offset. Therefore, slowing the spindle speed (increasing Trev) has less impact on the data rate than for conventional data layouts. Thus, lower speed disk drives can be used to support a given quality or number of A/V streams. Lower speed disk drives further reduce total acoustic noise.

The present invention improves the average performance of the disk drive 25 as measured by data rate, response time and access time. Further, the present invention significantly improves minimum data rates, maximum response time and maximum access time. These improvements afford more budget for error event management caused by environmental factors. External disturbances from shock or vibration can lead to excessive servo position errors or track miss-registration. This can lead to failure to read or write data on the first attempt. Read/write channel noise or spurious debris inside the HDA can also lead to such failure. These failures, when they occur, are referred to as error events and are usually managed by the disk drive in error

management events such that data are faithfully reproduced. Error management consumes time for retry attempts and other remedies. Reducing the systematic time to service A/V streams/data increases the time for managing error events and thus improves total data reliability for a given A/V bandwidth requirement. Improving said budget improves the reliability of disk drives in consumer applications by making them more fit for such use.

In addition, the present invention systematically reduces the need for aggressive time-optimal seek time performance using seek profiles described herein according to the present invention. By making this reduction, the seek servo system is redesigned to take advantage of the rotation time in a systematic manner. In so doing, additional improvements can be gained in seek acoustic noise reduction from the disk drive. Still further, demands on the disk drive system chassis design are reduced because seek reaction forces are reduced (chassis response to seek reaction forces can result in additional loss of response time performance.) This also makes the total acoustic noise generated by a disk drive less dependent on the system chassis and enclosure. And still further, the reduced performance required by the seek servo system allows the use of lower cost power amplifiers and motors.

Additionally, using the coherent phase layout the present invention provides symmetric forward and reverse sequential data segment DS access response time for 'trick-play' features. And, allows for reducing spindle spin speed with less loss in average and minimum data rates than compared to conventional layouts such in FIG. 1. Lower spin speed will further reduce total disk drive acoustic noise and imbalance reaction forces transmitted through the system chassis that will still further reduce total acoustic noise. Lower spin speed also allows for a lower total cost disk drive.

In addition to use of the disk drive 25 in computer applications, a data segment

layout according to the present invention allows the use of the disk drive 25 for storing and retrieving AV content in e.g. an AV storage server. FIG. 9 shows a block diagram of an example AV storage server 102 according to the present invention. The AV storage server includes a controller 104, at least one buffer memory 106 and one or more storage devices 108 such as disk drives 25. The disk drives 25 can store AV information for various video titles such as movies. The controller 104 controls the reading and writing of data to the disk drives 25. AV data read from one or more of the disk drives 25 can be output from the AV storage server for display on a display 110 connected to the AV storage server 102. Each disk drive 25 can simultaneously or sequentially provide AV information to one or more AV streams output from the AV storage server 102. Further, incoming AV data into the AV storage server 102 (e.g. from a cable or over a network) can be stored onto one or more of the disk drives 25. Each disk drive 25 can simultaneously or sequentially store AV information from one or more AV streams incoming into the AV storage server 102.

The AV storage server 102 can be a component of an AV system 112 according to the present invention, wherein the AV system 112 comprises said AV storage 102 including an interface unit 114, a wired communication network 116 and component boxes 118 such as consumer electronics equipment. The AV system 112 can be a part of a home network system with connection to external cable or network for receiving AV information. One or more component boxes 118 can receive AV content from one or more disk drives 25 in the AV server. AV data is read from the disks 38 in the disk drives 25 to produce data streams which are transmitted to component boxes 118 or displays 110 for viewing. Further, one or more component boxes 118 can provide AV content to one or more disk drives 25 in the AV server 102. The data streams can comprise sequences of discrete fragments of data which are periodically transmitted in bursts so that over time a constant stream of data is transmitted. The data stream can be smoothed out using the buffer memory 106. In one example, each burst of video

data can corresponds to about 0.5 to 1.0 second of video for a magnetic disk drive 25.

The present invention improves the systematic reliability of response time and consequently the sustained data rate or throughput, taking into account the electro-mechanical nature of the disk drives 25. At the same time the present invention preserves the random access nature of a disk drive, and the new benefits derived therefrom for the storage of AV content described above.

In another aspect the present invention provides a method for storing a stream of data to the data storage disk so as to obtain a nearly constant data storage transfer rate when reading the data from the data storage disk. FIGS. 10-11 show example flowcharts of processes for implementing an embodiment of the of present invention. To best understand the processes, the reader should also refer to FIGS. 2-4. In one implementation, the processes can take the form of computer programs typically executed by well-known data processing and control electronics including microprocessors or microcontrollers 80, 14 (e.g., PD787012 microcontroller manufactured by NEC). In one example, the computer programs can be executed by the microcontrollers 80 or 92 in response to data storage and retrieval commands from a processor 14. From the depicted flow charts, those skilled in the art can readily select an appropriate microcontroller and program the selected microcontroller to execute the disclosed processes.

Referring to FIG. 10, in one embodiment, the method of storing a data stream includes the steps of partitioning incoming data into data segments (step 120); moving the data segments into a buffer 86 or 16 (step 122); for each data segment: identifying one or more data tracks on the data storage disk to store a data segment (step 124); directing the VCM to position the transducer over the identified tracks (step 126); and recording that data segment in the identified tracks with coherent phase relative to other

data segments according to the data segment pattern herein, wherein the start phase for each data segment is the same, and the end phase for each data segment is the same (step 128). In one example, steps 120, 122 can be executed by the processor 14, and steps 124, 126 and 128 can be executed by the drive electronics 26 (e.g., microprocessor 80 or data controller 92). Other functional division of the computer program for execution by various processors and microcontrollers in the disk drive 25 and other system processors such as the CPU 14 are also possible and contemplated by the present invention.

As such, in one scenario, a data stream is received by the disk drive 25 as bytes of data, and segmented into sectors. A set of sectors is grouped into a data segment by the disk drive electronics chip 84. The data segment is stored into a disk drive buffer 86, and the microprocessor 80 identifies the tracks on the data storage disk 38 to store the data segment. The servo controller 94 positions the transducer 64 over the identified tracks, and the data segment is stored onto the tracks according to the coherent phase data segment pattern/layout herein.

In step 128, the data segments can be recorded such that the data tracks in each data segment are offset by a predetermined skew angle α. Preferably, the skew angle is selected to minimize rotational latency as the transducer is positioned over adjacent tracks within a data segment to write data thereto and later read data therefrom, in a forward sequential fashion. Due to the coherent phase layout/pattern, the data segments are recorded so as to obtain a nearly constant data storage transfer rate when transferring data to/from the storage media (e.g., data disk). In another embodiment of the present invention, the steps shown in FIG. 10 can be performed, sequentially or simultaneously, to store multiple data streams onto the data disk drive 25.

Referring to FIG. 11, the data segments can be read from the data disk 25 in response to data segment requests from a processor 14. Upon receiving a request for a data segment stored on the disk 38 (step 130), the data tracks where the data segment is stored are identified (step 132); the VCM is directed to position the transducer over the identified tracks (step 134); and data is read from the identified tracks into a buffer 86 or 16 to be transmitted to the requester (step 136). The data segments read from the disk can be combined to reformulate an output one or more data streams (step 138).

As such, in one scenario, the data segments can be read from the disk drive 25 in response to host command(s). The disk drive electronics chip 84 receives the request for data segment. The microprocessor 80 identifies the location of the data tracks on the disk media where the data segment resides, and the servo controller 94 positions the transducer 64 over the identified tracks. The data is read, in form of a data segment, one sector at a time, from the tracks and stored into the disk drive buffer 86. When a certain amount of data has been stored in the buffer 86, the data is reformulated and transmitted across the disk drive interface.

The steps in FIG. 11 can be performed, sequentially or simultaneously, to read data segments for multiple data streams from the disk, and reformulate the data streams for output. In one example, steps 130 and 138 can be executed by the processor 14, and steps 132, 134 and 136 can be executed by the drive electronics 26 (e.g. microprocessor 80 or data controller 92). Other functional division of the computer program for execution by various processors and microcontrollers in the disk drive 25 and other system processors such as the CPU 14 are also possible and contemplated by the present invention. The processes described in relation to FIGS. 10-11 can also be implemented in the system 102 of FIG. 9.

The data/track layout method of the present invention allows organizing and allocation of disk drive capacity when used to store and retrieve isochronous Audio-Video (AV) content for consumer electronics applications. The layout model can be particularly useful when managing multiple AV streams over multiple content objects in a full and fragmented disk drive. The method is not dependent on any particular interface, and can be implemented on e.g., ATA, SCSI, 1394, etc.. Using FCP-AV/C with an on board Stream Manager and Embedded File System can be used with the method of the present invention e.g. for content objects used for delay broadcast applications.

A coherent phase layout according to the present invention is laid out on the disk 38 such that data can be stored on the disk 38 according to that phase layout (e.g., the segments have coherent relative rotational phase). Servo information provides track location and angular position of data on the disk 38, allowing specification of an address for every sector on the disk, wherein a collection of sectors makes up a segment DS. Therefore, the servo information provides radial position and angular position of each segment DS on the disk 38. The start of each track is recorded on the disk 38 at fabrication, such that when data is later written in segments DS on the disk 38 by the servo system, the data is stored in segments having relative coherent phase. As such, the coherent phase pattern is an attribute of the fabricated layout pattern on the disk 38. In one example, the disk 38 of the disk drive 25 is initially formatted with S-Scan using the coherent phase pattern layout described herein and shown by example in the drawings. Thereafter, an LBA to physical transformation module in the disk drive firmware maps data segments according to the coherent phase data segment pattern herein.

According to the present invention, the rotational phase between the end of one data segment to the start of another data segment, has a limited range of

predetermined possibilities or in a special case it is constant. The servo system in implemented with information representing rotational time form end of one data segment to start of another data segment. According to the present invention, a data segment pattern with coherent phase is laid out on top of data layout, which is on top of the servo format. In conventional data layouts, there is no linkage from the servo system to the data layout, making it impossible to determine rotational time between end of a piece of data to start of another piece of data.

In one example operation, a read/write command is issued and translated into a specific sector or sectors which start at a logical block address. The logical block address is converted (mapped) to a physical location on the disk surface using information including e.g. the size of each data segments, number of tracks per data segment, number of sectors per track, mapping of the defects, track skew angle, etc.. Firmware, or software that controls hardware, uses said information to convert logical block addresses to physical locations based on the coherent phase layout according to the present invention. The disk drive 25 then uses head(s) within the head transducer assembly 64 for writing and reading magnetic patterns on the rotating magnetic storage disk 38 in the physical locations in one or more concentric tracks. A coherent phase segment layout/pattern according to the present invention includes segments DS such that each segment DS has a predetermined rotational phase relative to another segment DS.

For example, said relative rotational phase R for each data segment in FIG. 5 is the same (i.e., 360-α). The predetermined relative rotational phase R from a data segment to different data segments can be different and selected from a limited number of predetermined values. In the example LBAx and data segment DS layout described herein in relation to FIGS. 5-6, each data segment DS includes two tacks, and has the same relative rotational phase R (i.e., 360-α) to other data segments. However, a data

segment DS need not be larger than one track. This is particularly the case as linear densities for disk drives increase. Further, some applications are limited to less than one track.

For example, when using ATA disk drives, there is a standard limit of 256 sectors per command, which can be utilized as the size of a data segment DS. Referring to FIG. 12A, as an example, each data segment DS can be selected to be ½ track in length. In that case, there are two different predetermined relative rotational phases for each data segment DS . Predetermined rotational times (rotational phases R) from each data segment to another segment can be one of: (1) ½ a full rotation time (R=180 degrees), or (2) a full rotation time (i.e., R=one revolution or 360 degrees). The track-to-track seek time or skew angle is not applicable in this case, and the one track and head switch time are not necessary.

As such in the example data segment pattern shown in FIG. 12A, each data segment has a first relative rotational phase R relative to a first set of data segments, and a second relative rotational phase R relative to a second set of data segments. For example, the data segment DS0 has a first relative rotational phase R=360 degrees to a first set of data segments including data segments DS2, DS4, DS6, etc. And, the data segment DS0 has a second relative rotational phase R=180 degrees to a second set of data segments including DS1, DS3, DS5, DS7, etc.. Similarly, the data segment DS0 has a relative start phase of 180 degrees relative to data segments DS1, DS3, DS5, etc.. And, the data segment DS0 has a relative end phase of 180 degrees with relative to data segments DS1, DS3, DS5, etc.. Similarly, the data segment DS0 has a relative start phase of 0 degrees relative to data segments DS2, DS4, DS6, etc.. And, the data segment DS0 has a relative end phase of 0 degrees with relative to data segments DS2, DS4, DS6, etc..

Further, all tracks need not have the same number of segments DS because there can typically be several (e.g., 16) recording zones (e.g., FIG. 6B) that include different number of sectors per track. As such, the number of segments DS in each track can vary from zone to zone. For example, the number of different relative start, end and rotational phases for data segments in each zone can increase from zones at the inner diameter to the zones at the outer diameter of the disk surface. The number and values of relative start, end and rotational phases for data segments in each zone can be selected as described by example herein to obtain one or more of the advantages of the layout format described herein.

As such, each zone includes a set of data segments therein with coherent phase selected for that set. In FIG. 6B, two of a plurality of recording zones 91 are shown. The inner recording zone includes an example data pattern layout such as shown in FIG. 12A wherein each track 74 includes two data segments. The outer recording zone includes an example pattern layout such as in FIG. 5 including data segments DSi and DSj where each data segment includes two tracks 74, and further shows start S and end E of each of the data segments DSi and DSj. Though in FIG. 6B, the layout patterns in the inner and the outer recording zones are different, in other versions the layout patterns in the recording zones can be the same wherein: in one case in all recording zones 91 each data segment DS includes one or more tracks 74, in another case in all recording zones 91 each track 74 includes two of more data segments DS, etc..

FIG. 12B shows another embodiment of a data pattern layout in a linear fashion, according to the present invention, wherein each data segment is one-third track in size. For example, track TKn+2 comprises three data segments DS56, DS57 and DS58 (track and DS numbers are randomly selected for purposes of example only). In one version, in a disk with multiple recording zones (e.g., FIG. 6B), a first zone on a

recording surface of the disk can include the pattern layout of FIG. 12A and a second zone on that recording surface can include the pattern layout of FIG. 12B. Yet in another version, where the disk includes multiple recording zones, and each data segment DS includes one or more tracks (e.g., FIG. 5), the number of tracks per data segment can be different in different recording zones. Further, the present invention contemplates a recording surface with different recording zones, wherein in at least one recording zone each data segment includes one or more tracks (e.g., FIGS. 12A-B), and in at least another recording zone each track includes two or more data segments (e.g., FIG. 5).

For pattern layouts such as shown by example in FIGS. 12A-B, where the relative rotational phase between segments has one of several predetermined values, the seek time for seek operations between segments in each recording zone can have one or more predetermined time values based at least on the values of the relative rotational phases (e.g., seek time can be a linear function of inter-segment rotation time). The seek time can also be selected to be a maximum, minimum, or combination of said predetermined time values for all seek distances. For example, for the pattern of FIG. 12A, the seek time can comprise the predetermined rotational times from each starting data segment to a destination data segment, including: (1) time for ½ a full disk rotation time (R=180 degrees), or (2) time a full disk rotation time (i.e., R=one revolution or 360 degrees).

The seek time for each seek operation between two segments in FIG. 12A is obtained based on the rotational time from the track where the starting data segment ends to the track where the destination data segment starts. In one example, the predetermined seek time between each pair of segments (e.g., identified by unique number or location on reference disk) is stored in memory to access and use by the servo loop. For example the servo controller 94 can access a seek time table (stored in

memory 86, or within the servo controller 94, or on the disk, etc.) for each recording zone, wherein each seek time table includes information representing the predetermined seek time for each pair of data segments in that recording zone. In another example, the predetermined seek time between each pair of segments is obtained from the inter-segment rotational time between the two segments based on e.g. the angular location of the end of the starting segment and the angular location of the start of the destination segment on the recording surface of the disk.

Though in the embodiments described herein a disk drive is used as an example of a data storage system or data storage device, other examples are possible. For example, the present invention can be implemented in other data storage devices such as e.g. CD player, DVD, CD ROM, etc.

The present invention has been described in considerable detail with reference to certain preferred versions thereof; however, other versions are possible. Therefore, the spirit and scope of the appended claims should not be limited to the description of the preferred versions contained herein.